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ENGINE OPERATION IN FLIGHT FOR MINIMUM FUEL CONSUMPTION

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SUMMARY

Engine and airplane performance data have been gathered from various sources and analyzed to determine indications of the most economical methods of flight operation from a consideration of fuel expenditure. The analysis includes the influence of such factors as fuel-air ratio, engine speed, engine knock, altitude, cylinder cooling, spark timing, and limits of cruising brake mean effective pressure.

The results indicate that the cheapest power is obtained with approximately correct mixture at low engine speed and highest permissible manifold pressure. If more power is desired, the methods of obtaining it are, in order of fuel economy: (a) Increasing the engine speed and maintaining safe cylinder temperatures by cooling; (b) retarding the spark or cooling further to permit higher manifold pressure; and (c) riching the mixture.

The analysis further shows that the maximum time endurance of flight occurs at the air speed corresponding to minimum thrust horsepower required and with minimum practicable engine speed. Maximum mileage per pound of fuel is obtained at slightly higher air speed. The fuel-air ratio should be approximately the theoretically correct ratio in both cases. For an engine equipped with a geared supercharger, as in the example presented, and with knock as the limiting condition, a comparison of operation at sea level and at 6,000 feet shows flight at altitude to be more economical on the basis of both range and endurance.

INTRODUCTION

The present-day requirements of length and endurance of flight have made fuel economy a subject of considerable importance in both military and commercial service. A

great deal of discussion of this subject has appeared from time to time; in such discussion, the problem is treated mainly from the standpoint of the manufacturer and the details of flight operation are considered to be more or less secondary and incidental. A large part of this problem may be solved in the aircraft factory; yet, with a well-designed airplane and engine, much of fuel cost lies within the control of the pilot, who has at his command various means of power control and knock suppression each of which imposes its own expenditure of fuel. As the power requirements in flight are increased, certain sacrifices in fuel economy must be made in order that the hazards of knock and excessive engine temperatures and pressures may be avoided. Common methods of safeguarding the engine from these hazards are throttling and riching the mixture. Other methods, less commonly used, are engine cooling and spark control. The influence of each of these factors on fuel economy is a matter of common knowledge, but the relative magnitudes have apparently not been generally appreciated. The purpose of the present paper is to present a quantitative analysis of the relative effects on fuel consumption of these various methods of safeguarding the engine in flight.

METHODS

The airplane chosen for this analysis is a Martin XB-10 equipped with two Wright R-1820-G engines, each developing 850 horsepower at 2,100 r.p.m. at sea level. Because of the lack of knock data on the R-1820-G engine or on other engines of the same type, the data on the variation of maximum permissible manifold pressure (as limited by knock) with engine conditions were obtained from tests on single-cylinder, liquid-cooled test engines (references 1, 2, and 3). These data, with the exception of those of reference 3, were corrected to the compression ratio (6.45) of the R-1820-G engine by a method proposed by Rothrock (reference 1) and incorporated with the R-1820-G calibration data. The effect of temperature rise across the supercharger was included. Although the procedure of applying single-cylinder data to the multicylinder engine may be questionable from a quantitative point of view, the trends should be fundamental to all engines of the general type being considered. Specific fuel-consumption values for all manifold pressures and engine speeds were determined by a method suggested by Schey and Clark in reference 4. Conversions of horsepower to air speed were made on the

basis of propeller tests by Biermann and Hartman (reference 5) and of charts published by Weick in reference 6. Curves involving cylinder temperatures and engine cooling were computed from curves presented in reference 7, in which parameters were derived in cooling tests of a Wright 1820-G cylinder.

ANALYSIS AND DISCUSSION

Factors Affecting Power Limitations

Imposed by Engine Knock

Fuel-air ratio.- The effect of fuel-air ratio on the specific fuel consumption of an 1820-G single-cylinder test unit is shown in figure 1(a), which was taken from reference 4. The specific fuel consumption increases with the mixture strength from its minimum value at a fuel-air ratio of 0.065 to a value 63 percent higher at a fuel-air ratio of 0.10. Unfortunately, the mixture that gives the best specific economy also produces high cylinder-head temperatures, as shown in figure 1(b) for both constant power and constant throttle. These cylinder-head temperatures were computed from equations presented in reference 7 for the 1820-G cylinder. Figure 1(c), which was taken from reference 3 shows that, with approximately this same mixture, permissible manifold pressures as limited by knock are minimum. This mixture, though disadvantageous from consideration of cylinder temperatures and knock, will hereinafter be called the optimum mixture because of its favorable fuel economy.

Figure 2(a) shows the effect of fuel-air ratio on the cooling cost in horsepower of maintaining a cylinder-head temperature of 350° F. on a Wright 1820-G cylinder. The temperature of 350° F. is considered as an average temperature over the head surface, the hottest point being 50° F. higher. The maximum cost, occurring at a fuel-air ratio slightly higher than the optimum mixture and at maximum power, is only 1.5 percent of the total brake horsepower per cylinder. In figure 2(b) may be seen the comparative cost of riching from the optimum mixture to a fuel-air ratio of 0.10. The fuel-flow rate with the optimum mixture is 62 percent of that with the richer mixture, and the inclusion of the cost of cooling to maintain constant cylinder-head temperature leaves this comparison practically unchanged, as shown in the figure. The extravagance of

cooling with rich mixtures is apparent. If the cowling is provided with controllable flaps, the necessary cooling may be obtained by opening the flaps. Data in reference 8 show that a pressure drop equal to the total velocity head of the free-air stream is available for cooling with a pump efficiency of little less than 1.0. Figure 3 shows the variation with air speed of the velocity head of the free-air stream at sea level and at 6,000 feet. The necessary pressure drop for cooling (fig. 2(c)) is shown in figure 3 to be available at air speeds as low as 130 miles per hour at sea level or at about 145 miles per hour at 6,000 feet.

Engine temperatures and cooling.- Figure 4 shows the effect of engine speed and engine temperatures on maximum permissible manifold pressures as limited by engine knock. The increase in allowable manifold pressure with decrease in inlet and cylinder-head temperatures is quite marked. Figure 4(a) was obtained from reference 2 and figure 4(b) from reference 1. The assumed linear relationship in figure 4(a) is substantiated by Edgar's data as shown in reference 1.

Cooling has previously been shown to be economically superior to mixture riching in avoiding excessive engine temperatures. Figure 4(a) indicates that the manifold pressure and, consequently, the power may be increased by reducing the cylinder-head temperature. This power increase is offset to some extent by the increased drag horsepower involved in cooling to lower cylinder temperatures. It must be recalled that the drag horsepower shown in figure 2(a) was necessitated by the maintenance of a constant cylinder-head temperature. The drag produced by cooling to lower temperatures is considerably greater. For example, assume that the two engines of the bomber are developing 1,680 brake horsepower (2,100 r.p.m.) with the optimum mixture. If an available cooling pressure drop of 20 inches of water is assumed, computations (reference 7) show that the cylinder-head temperature may be reduced from 350° to 280° F. (cooling-air temperature, 70° F.) with a sacrifice of 98 horsepower (18 cylinders) but with a gain of 180 horsepower due to receding knock limits. The net gain therefore is 82 horsepower. This situation is expressed graphically in figures to be presented later.

Engine speed.- Figure 4(a) also shows that engine speed may be quite a significant factor in determining the knock limits of manifold pressure for constant spark ad-

vance. It is apparent that, aside from power increase with engine speed due to increased displacement per unit time, there is additional allowable power increase due to receding knock limits at higher engine speed. The variation of this tendency with different fuels in common use should not affect the general conclusions that will be drawn from this discussion.

Spark setting.- The spark advance angle is quite generally known to be related to engine knock, the retarded spark permitting higher manifold pressures. Figure 5(a) shows the magnitude of this effect with a single-cylinder test unit having a pent-roof combustion chamber. It is indicated in the figure that the process of increasing allowable manifold pressures by spark retardation is attended by a corresponding increase in power (fig. 5(b)) at a considerable sacrifice of fuel economy (fig. 5(c)). The significance of these trends will be discussed later.

Engine Operation in Flight

Conditions remote from engine knock.- Figure 6 shows sea-level calibration curves of the Wright R-1820-G engine. Curves defining knock limits based on figure 4 are included. The effect of engine speed is assumed to be the same for the two fuel-air ratios in question. In the study of engine operation in flight, the power requirements of the airplane in question must be known. Figure 7 shows the thrust power required to maintain a Martin XB-10 airplane in level flight at various engine speeds as a function of air speed. At sea level, a minimum of 220 horsepower is necessary for flight. From references 5 and 6, an engine output of 275 brake horsepower is found to be necessary to obtain the required 220 thrust horsepower. The minimum fuel flow for this power is obtained with the optimum mixture (fig. 6(a)) and at the minimum practicable engine speed which, in this case, is considered to be 1,100 r.p.m. These conditions are located at point 1 in figure 6(a). The most economical method of increasing the power from point 1 is evidently to increase the manifold pressure and, at the same time, to adjust the propeller blade-angle setting to maintain constant engine speed (1,100 r.p.m.) until knock is approached, say at a manifold pressure of 26.3 inches of mercury and with a cylinder-head temperature of 350° F. (point 2 in fig. 6(a)). Cylinder-head temperatures should be controlled by cooling rather than by employing rich mixtures (see fig. 2(b)) un-

less the cooling is found to be inadequate with flaps fully open.

Conditions close to knock.- When further power increase is no longer safely possible by increasing the manifold pressure at the minimum practicable engine speed and given spark advance because of approaching knock conditions, the following options for increasing the power remain: (a) Increasing the engine speed, (b) retarding the spark (fig. 5), (c) diminishing the engine temperatures by cooling (fig. 4(a)), and (d) riching the mixture (fig. 1(c)). Options (b), (c), and (d) allow power increase by raising the manifold-pressure limits, while option (a) increases the power mainly by increasing the amount of displacement per unit of time and, according to figure 4(a), to some extent by permitting higher manifold pressures. The carburetor-air temperature is regarded as constant. Of the choices listed, option (a) will later be shown to be the most economical. This course of operation is illustrated by the heavy line connecting points 2 and 3 in figure 6(a). The cylinder head is kept at a constant temperature of 350° F. by controlled cooling. At maximum engine speed (point 3, fig. 6(a)), suppose that the power is further arbitrarily increased by cooling to point 4. Figures 3 and 8(c) show that, at this point, a pressure drop of 20 inches of water is available for cooling. Computations previously referred to show the gross magnitude of this increase to be 180 horsepower (2 engines) and that the cylinder head may be cooled to 280° F. The total cooling cost of 98 horsepower reduces this gain to 82 horsepower. Further increase in power may be obtained by riching (option (d)). This step terminates at point 4' in figure 6(b), in which the same procedure was used as in figure 6(a) except that the mixture has a fuel-air ratio of 0.10. The points 1', 2', etc. in figure 6(b) correspond to points 1, 2, etc. in figure 6(a). At all of these points except 1 and 1', spark retarding may have been resorted to for further power gain by shifting the knock limits.

Figure 8(a) summarizes the relative fuel costs of the various options for increasing the power. The economy of these steps is indicated by the slopes of the curves, the numerical values of which are given in table I. For those options in which air cooling is involved, the cost in horsepower is shown in figure 8(b). In this figure may be seen the small cooling cost of maintaining a constant cylinder-head temperature of 350° F. as the engine speed was

increased (steps 2-3 and 2'-3'). The rapidly mounting cooling cost of reducing the cylinder temperatures is also shown (steps 3-4 and 3'-4'). The lower pressure drops indicated in figure 8(b) may be obtained by cowling-flap control. Low pressure drops at low air speeds may exist during climb where cylinder temperatures may be correspondingly higher and gross and net power gain from cooling correspondingly reduced.

Retarding the spark at point 2 is shown in figure 8(a) to be more economical than riching but more costly than increasing the engine speed at constant cylinder-head temperature. At point 3, the small power increase due to cooling is accomplished at slightly greater fuel cost than by retarding the spark over the same range. At point 4, the preference of spark control to riching is again obvious. Retarding the spark, although not regarded as a means of obtaining considerable increase in power, may be resorted to in cases where a little more power is desired near the knock condition without excessive fuel expenditure. The same small increase in power obtained by riching the mixture would prove more costly as this analysis shows. In this respect, reducing cylinder temperatures is likewise preferable to the use of richer mixtures.

Although these trends are only illustrative and different values should be obtained with different engines and fuels, such large differences in fuel economy exist among several of the methods of operation discussed that certain general conclusions can be drawn. It is apparent that the most economical method of operation is with maximum allowable manifold pressure and minimum practicable engine speed. The methods of obtaining further power increases are, in the order of fuel economy: (a) Increasing the engine speed, (b) retarding the spark or introducing further cooling to permit higher manifold pressures, and (c) riching the mixture. Retarding the spark and introducing further cooling seem to require sacrifices so nearly equal as to make the choice of a preference somewhat difficult. Power made available by cooling is small compared with that obtained by retarding the spark. Both methods, however, are definitely superior to riching the mixture.

The dashed lines marked "full throttle" in figure 6 indicate that the discussion thus far has dealt with part-throttle operation, engine knock having prohibited higher manifold pressures. For cruising, in addition to engine

knock, the brake mean effective pressure limitation recommended by the engine manufacturer for maximum engine life may enter into the data presented in figure 6. For the particular engine under discussion, this limit has been placed at 137 pounds per square inch and is represented in figure 6 by dashed curves marked "cruising limit, 137 brake mean effective pressure." Operation within this limit largely obviates the knock hazard for this engine, leaving, in the main, the economy only of steps 1-2 and 1'-2' to be considered; other power gains for cruising will be made at constant limiting brake mean effective pressure. Figure 8(a) indicates this procedure to be more costly than adherence to the subknock limit in cases where engine life is of secondary importance. Cases of this sort arise especially in military operations, such as bombing expeditions, in which reduced fuel load permits an increased munitions cargo and time between engine overhauls is a lesser consideration. Furthermore, the speed requirements of certain long-range flights may demand higher mean effective pressures than those recommended, while fuel economy still remains a necessity.

Application to Airplane Performance

Figure 7 shows the thrust power required at sea level to maintain a Martin XB-10 airplane in level flight at various air speeds. From figure 7, figure 8(a), and data from references 5 and 6, the horsepower obtained in the procedure previously outlined is converted into obtainable air speeds and plotted against fuel flow in figure 8(c). Table I also includes the relative costs of airspeed increases for the steps indicated by points 1, 1', 2, 2', etc.

The mileage per pound of fuel is computed from figure 8(c) and plotted against air speed in figure 9. The maximum mileage is obtained at air speeds somewhat higher than those at which the hourly fuel consumption is a minimum. Riching the engine mixture (4-4') to a fuel-air ratio of 0.10 (fig. 8(a)) makes available a 12-percent increase in brake horsepower and a 4-percent increase in air speed at the cost of a 63-percent increase in fuel consumption. Obviously, operation in this range should be avoided unless this relatively small increase in air speed is essential. Spark control or cooling should, if feasible, be given preference to riching at all times.

<u>Maximum time endurance</u>.- The maximum time of flight is obtained in this example at the air speed where the power required for level flight is minimum at minimum practicable engine speed and with optimum mixture ratio. (See figs. 7 and 8.) As may be expected, the performance of an airplane changes appreciably during long flights owing to the continuous reduction of fuel weight. Figure 7 shows the difference in power required for the bomber with the fuel tanks full and empty. The solid curves of figure 8(c) refer to the empty condition while the short-dash curves apply to the condition at the beginning of a long flight in which the airplane is loaded to full fuel capacity. Figure 8(c), however, shows some differences in fuel consumption, especially at lower flight speeds. The conditions during flight obviously lie somewhere between the solid and the short-dash curves.

<u>Maximum range</u>.- The maximum range of an airplane, as indicated by the peaks of the curves in figure 9, is obtained between points 1 and 2 where the engine is operating at minimum speed and with the optimum mixture. Considerable variation in air speed for maximum range, of course, exists among airplanes of various types. For the airplane under discussion, the maximum range is found to occur at about 120 miles per hour without the weight of fuel supply or at about 140 miles per hour with the fuel weight added. (See fig. 9.)

<u>Minimum fuel consumption for a given air speed and altitude</u>.- The operating conditions for best economy at a given air speed depend, as shown in figure 8, on the closeness to the maximum output of the power requirement for the given flight condition. At the flight speed corresponding to the minimum power required, it has been shown desirable to operate the engine with approximately the theoretically correct (or optimum) mixture and at the lowest practicable engine speed. If the required air speed is at some higher value, the procedure in the previously outlined order of preference should be followed.

Effect of Altitude

By methods of analysis similar to those used for sea-level conditions, figures 10, 11, 12, and 13 have been plotted to determine the influence of altitude. The data were taken from the same sources as for sea-level conditions. Because of the lower carburetor temperatures and the de-

creased manifold pressures at altitude, the hazards of knock in this example are more remote at altitude. (Cf. figs. 6 and 10.) Figure 10(a) shows that the amount of supercharging employed produces manifold pressures at 6,000 feet barely sufficient to cause knock at full throttle. With the rich mixture (fig. 10(b)), the knock limits are even further removed from full-throttle operation. The necessity for obtaining power increase through the medium of cooling, spark control, or riching is also less likely. In the case presented (fig. 10), little is to be gained in the way of power increase by any of these three methods because maximum power is obtained with the lean mixture at full throttle without knock. With higher impeller-gear ratios, however, the additional methods of knock control would become necessary probably with the same order of preference as at sea level.

In the example presented, the supercharger being permenently geared to the engine crankshaft, the temperature rise across the supercharger was approximately the same at 6,000 feet as at sea level. If gear shifting or a turbo-supercharger were employed to increase impeller speeds at altitude, this temperature rise would be greater at altitude for a given manifold pressure with an increased knocking tendency as a result.

In the order of their economy, the methods of increasing power and air speed remain the same at 6,000 feet as at sea level. (Cf. figs. 8 and 12.) Figure 13 shows the same general trends as those noted in figure 9 for sea level. Comparison of these figures shows better mileage per pound of fuel at 6,000 feet for all flight conditions represented except at extremely low air speeds. Comparable data for higher altitudes were not available.

CONCLUSIONS

From the foregoing analysis the following conclusions are drawn:

1. The methods of increasing power in flight starting from minimum conditions of power requirement and fuel cost are, in order of economy:

(a) Increasing the manifold pressure at constant minimum practicable engine speed to the point of in-

cipient knock or to full throttle if knock is not encountered.

(b) Increasing the engine speed and the cooling within knock limits until the maximum engine speed is reached.

(c) Retarding the spark or reducing the cylinder-head temperatures to permit higher manifold pressures.

(d) Increasing the fuel-air ratio to permit higher manifold pressures.

2. For maximum time endurance, the airplane should fly at the air speed corresponding to the minimum horsepower required with lowest practicable engine speed and with approximately correct mixture. Maximum mileage per pound of fuel or maximum range, however, is obtained at slightly higher air speeds.

3. In the example presented, cruising under brake mean effective pressure restrictions recommended by the engine manufacturer is less economical than being limited only by knock.

4. For the engine-supercharger combination considered, with knock as the limiting condition, flight at 6,000 feet, except at extremely low air speeds, is more economical than at sea level on the basis of both range and endurance.

5. When the engine is operating near knock limits, power and air-speed increases made available by excessive cooling are relatively small.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 24, 1939.

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TABLE I

Relative Economy of Various Methods of

Engine Operation at Sea Level

(See fig. 8)

Condition	Step	Increase in horse-power, Δ hp.	Increase in fuel flow ΔW_f (lb./hr.)	$\Delta W_f/\Delta hp.$	Increase in air speed, ΔV (m.p.h.)
Increasing:					
Manifold pressure	1-2	305	107	0.351	67
Engine speed	2-3	875	441	.502	54
Cooling at optimum fuel-air ratio	3-4	82	59	.720	3
Increasing:					
Manifold pressure	1'-2'	395	214	0.5420	77
Engine speed	2'-3'	980	695	.709	55
Cooling at fuel-air ratio of 0.10	3'-4'	102	110	1.080	2
Riching mixture	2-2'	90	174	1.93	10
from optimum fuel-air ratio	3-3'	190	429	2.21	11
to fuel-air ratio of 0.10	4-4'	240	480	2.00	10

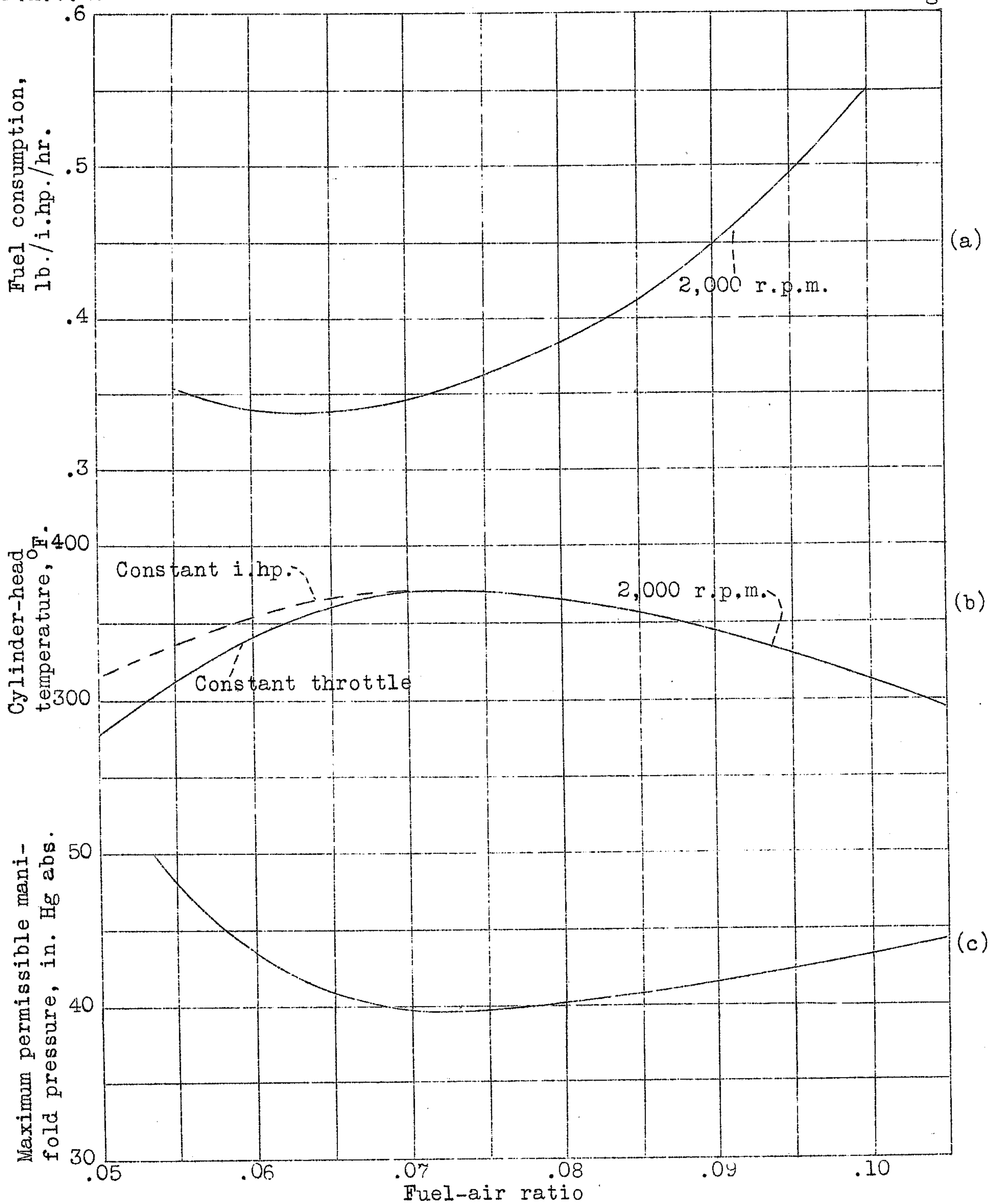


Figure 1.- Effect of mixture ratio on fuel consumption, cylinder-head temperature, and maximum permissible manifold pressure. (Curve (a) from reference 4; curve (c) from reference 3.)

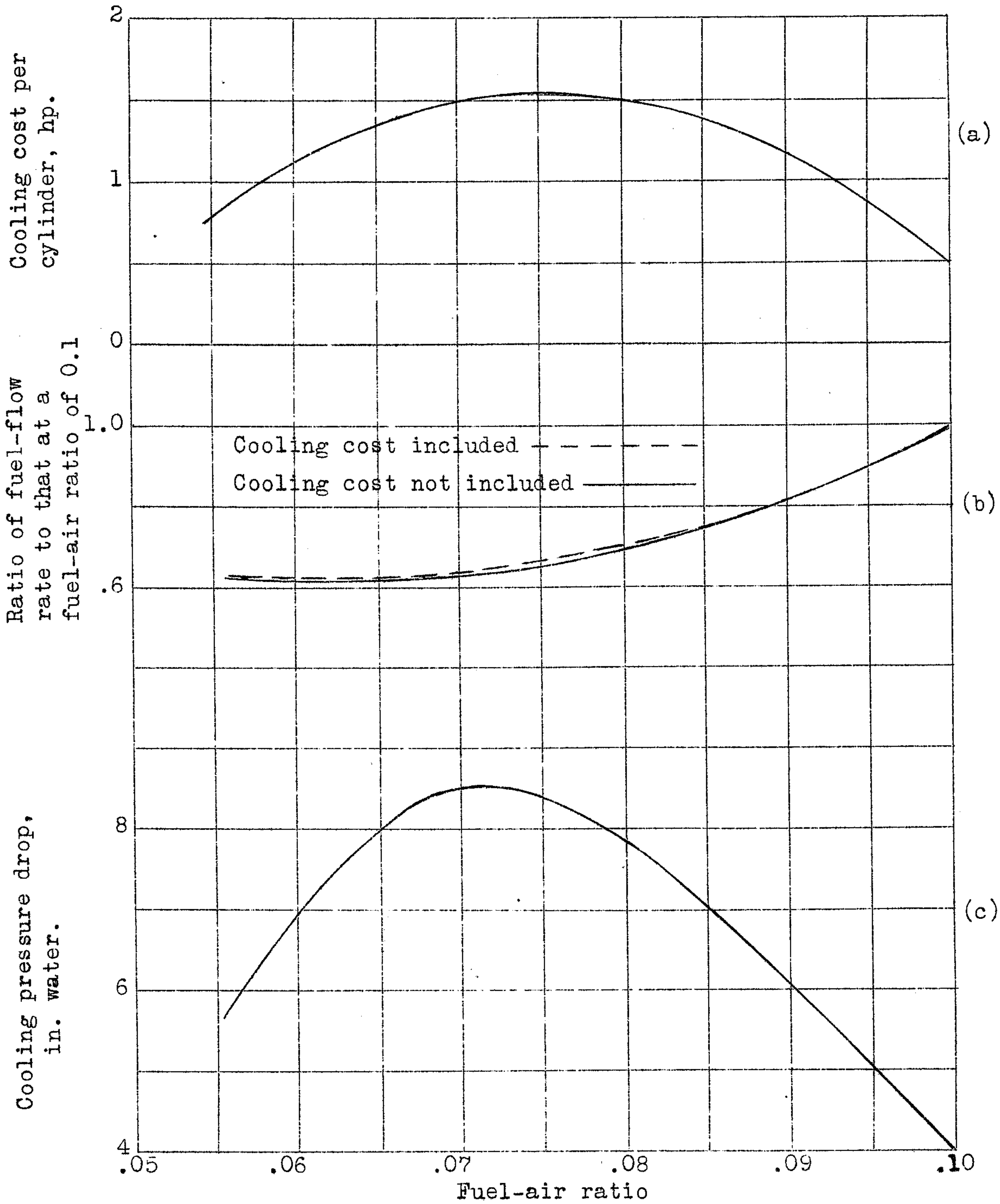


Figure 2.- Relative costs of maintaining head temperature at 350° F. by cooling with air or by using rich mixtures. Indicated horsepower, 115 per cylinder; sea level; total brake horsepower, 950 per engine.

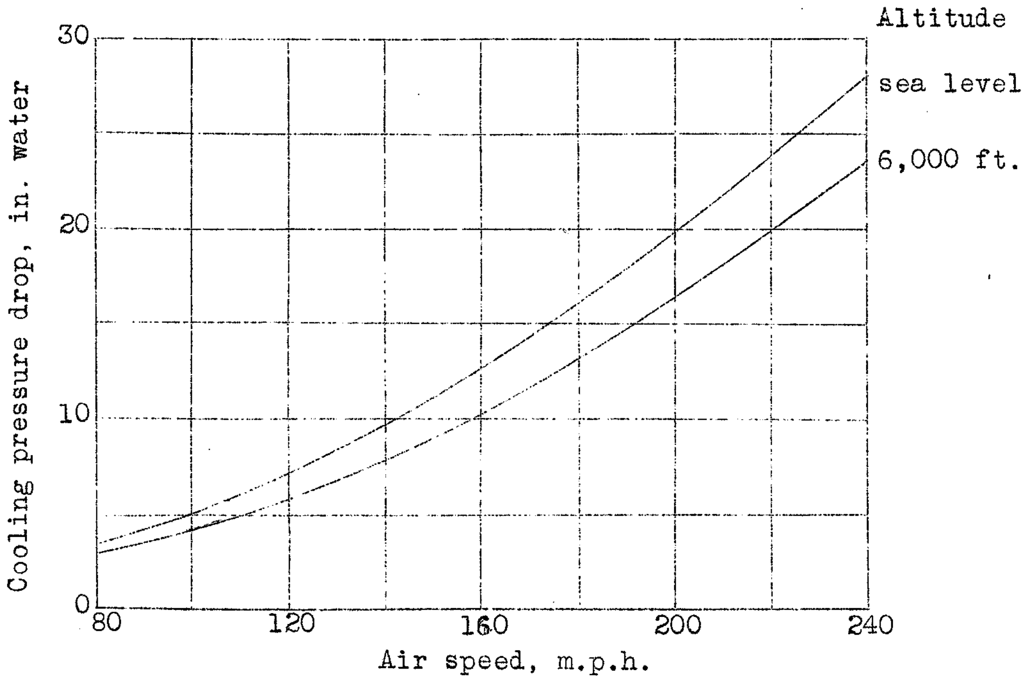
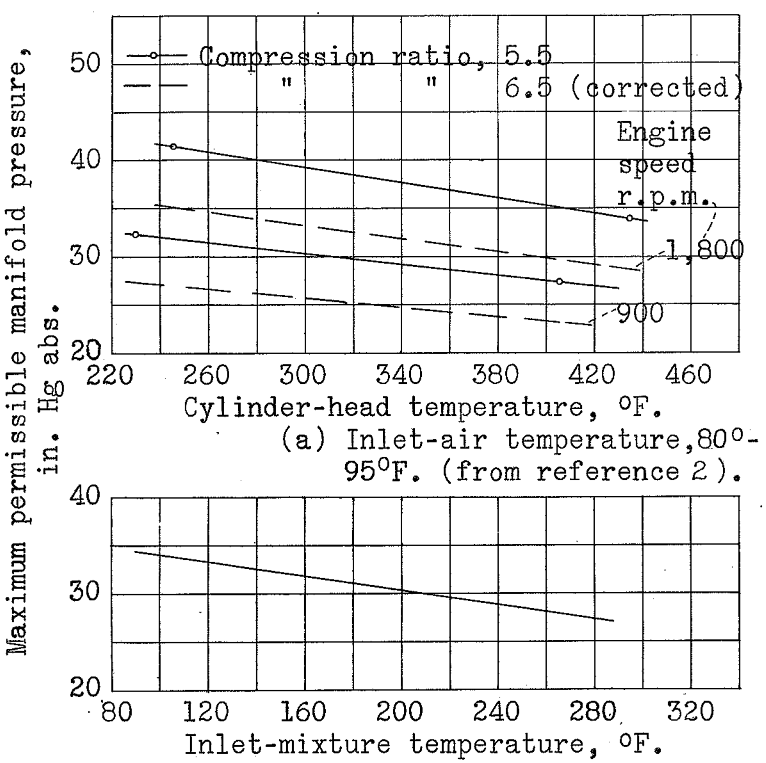


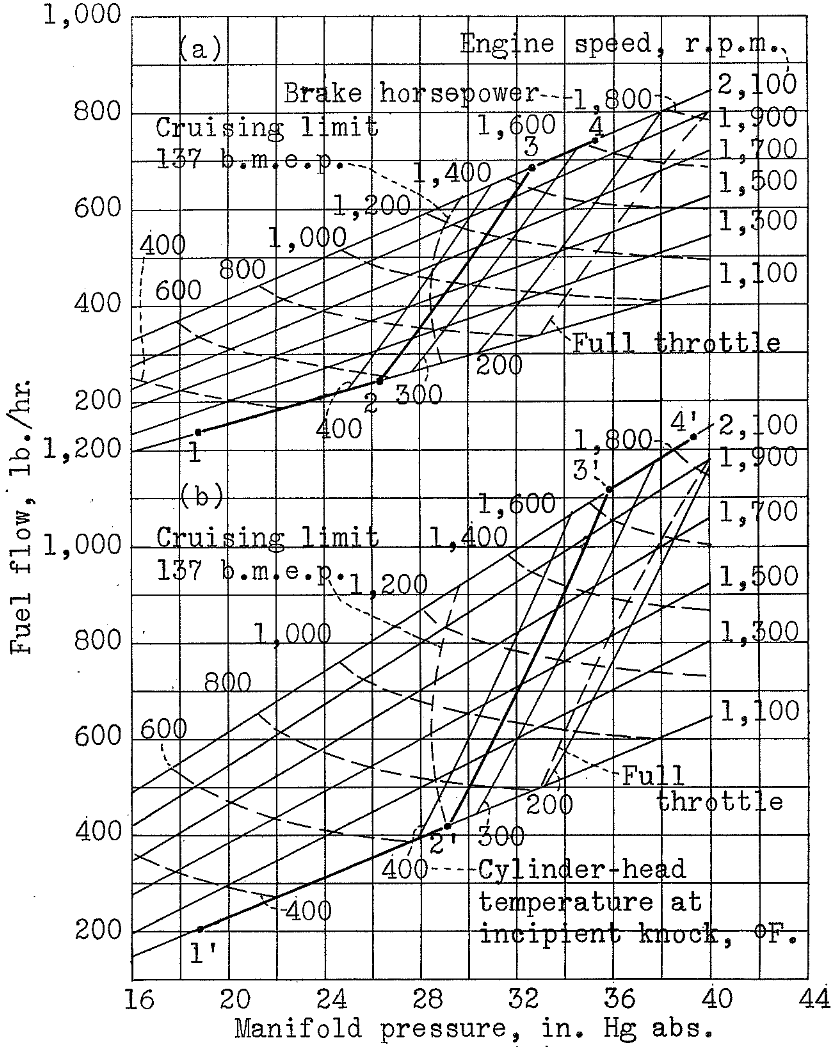
Figure 3.- Available cooling-air pressure drop across engine cylinders.



(a) Inlet-air temperature, 80°-95°F. (from reference 2).

(b) Compression ratio, 6.45 (from reference 1).

Figure 4.- Effect of engine temperatures on maximum permissible manifold pressure at two engine speeds. C.F.R. engine; 86-octane fuel; constant spark advance.



(a) Fuel-air ratio, optimum. (b) Fuel-air ratio, 0.10.

Figure 6.- Effect of manifold pressure, engine speed, and fuel-air ratio on rate of fuel consumption at sea level. Carburetor-air temp., 60°F.; impeller-gear ratio, 7.14.

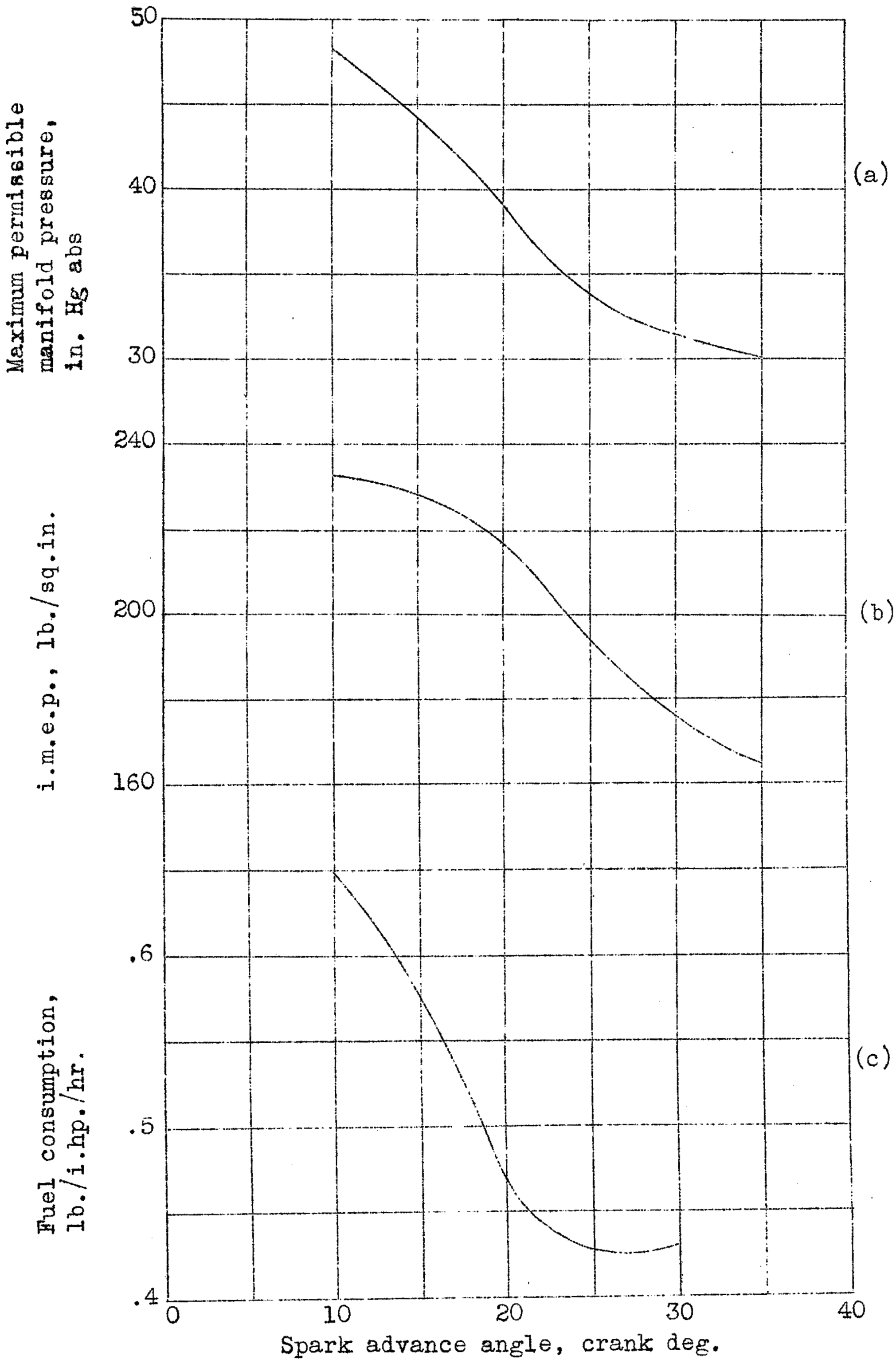


Figure 5.- Effect of spark advance angle on engine performance with constant knock. Single-cylinder test unit with pent-roof combustion chamber; 87-octane fuel; fuel-air ratio, 0.083; engine speed, 2,250 r.p.m.

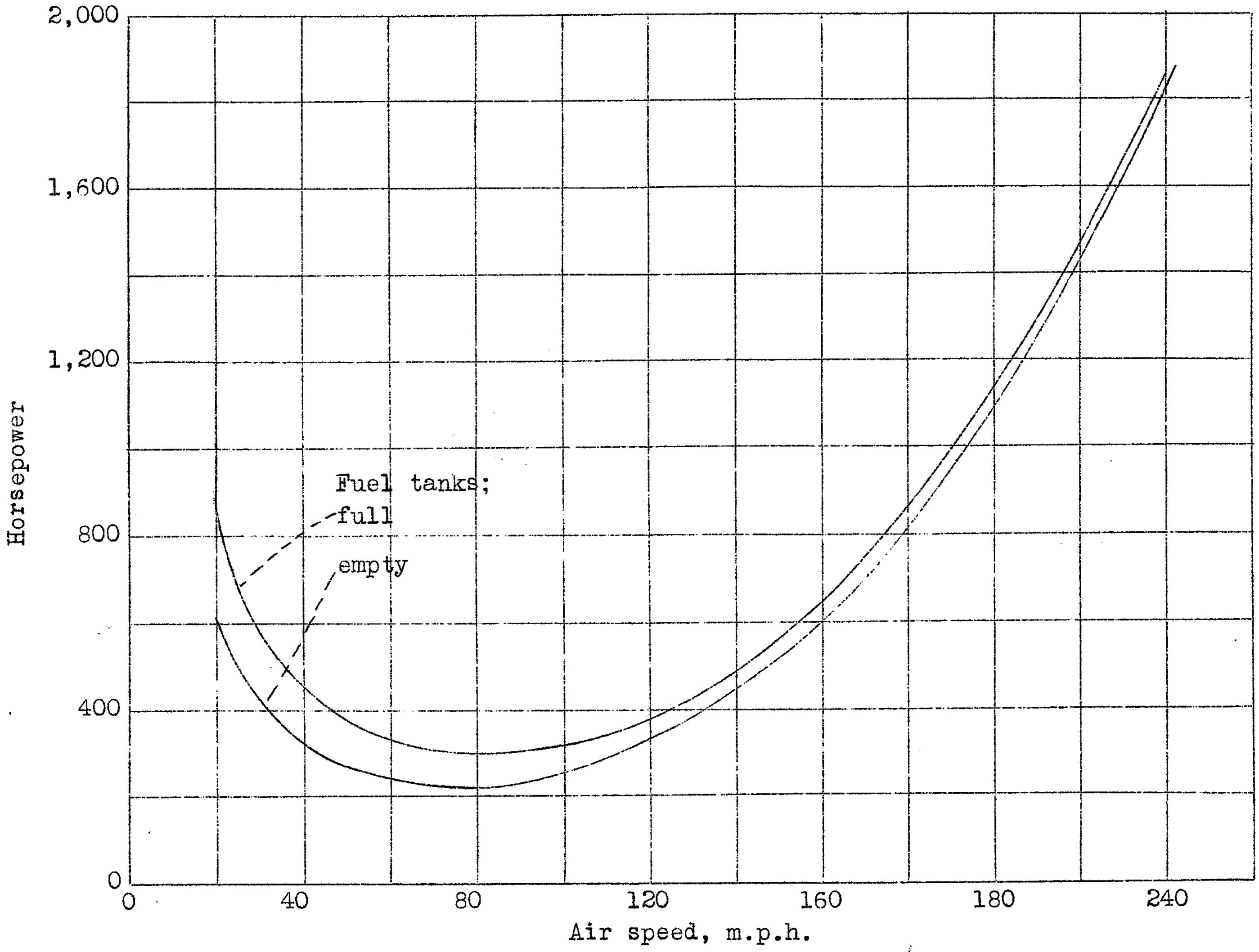
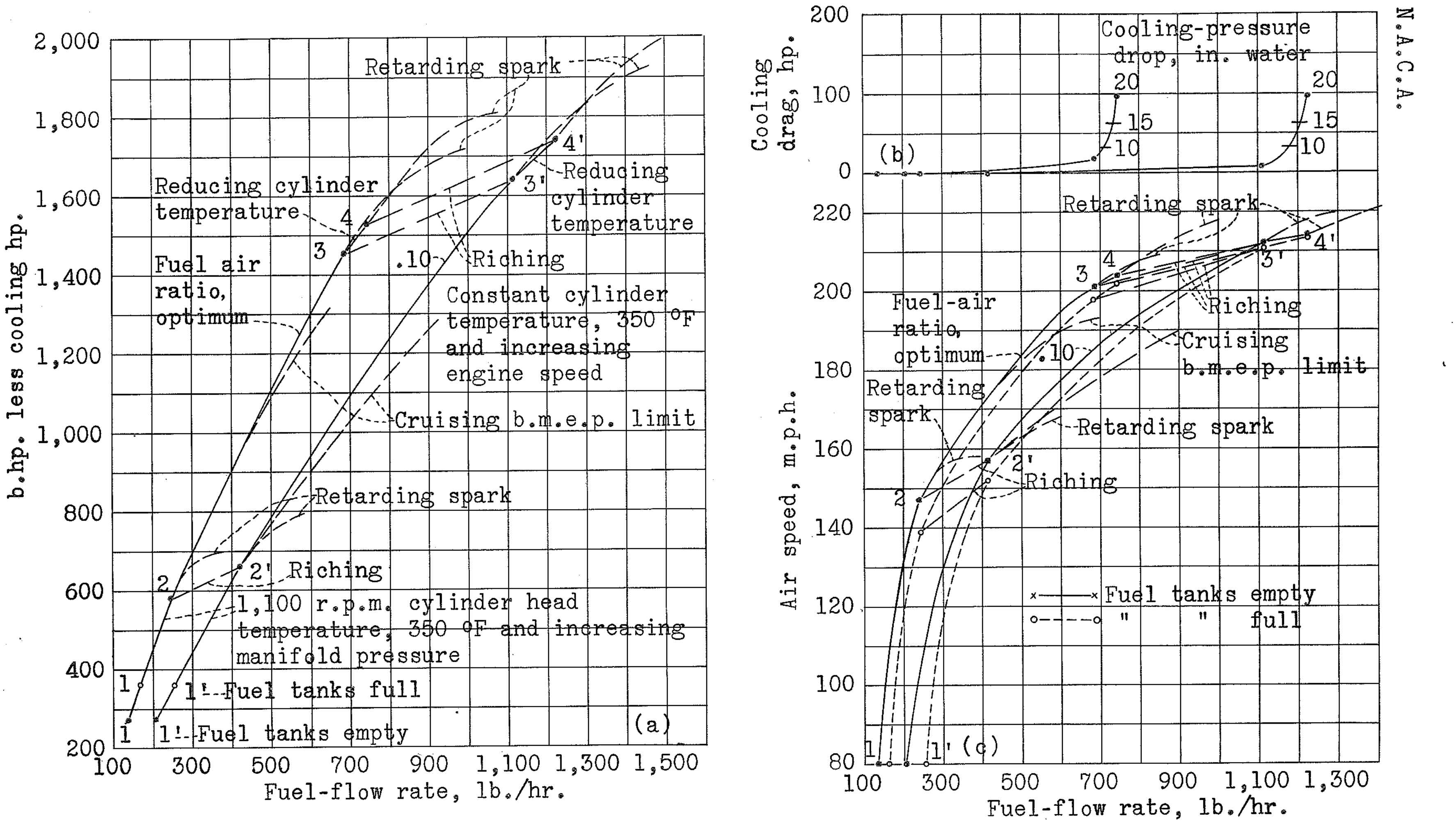
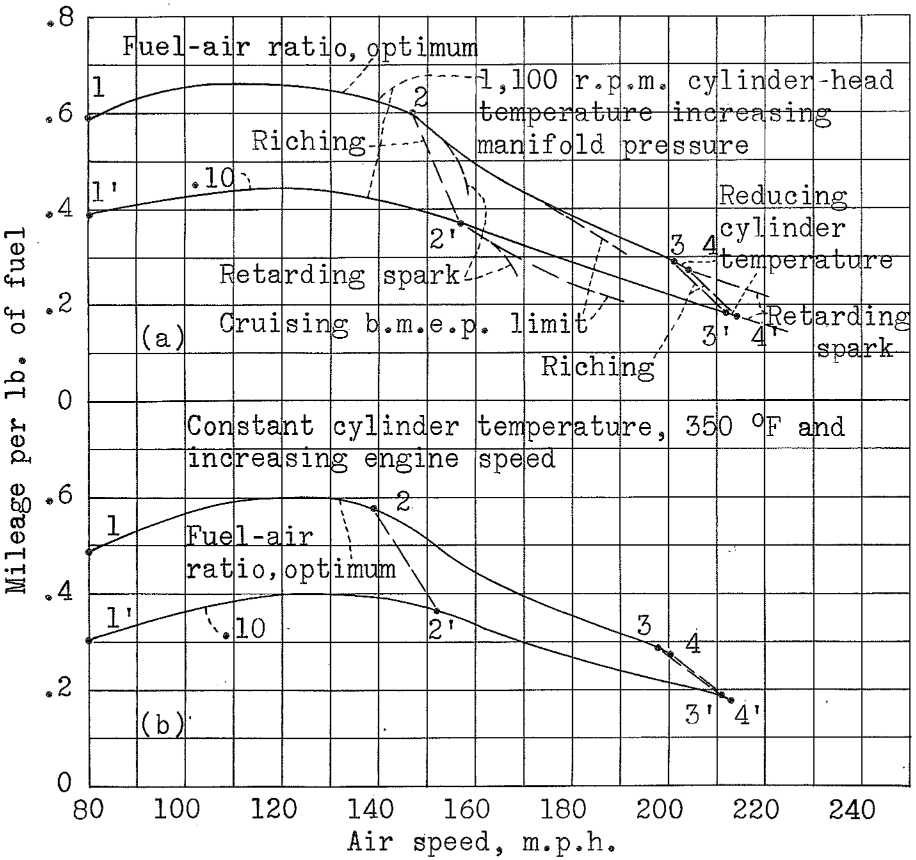


Figure 7.- Performance curves for Martin XB-10 at sea level.

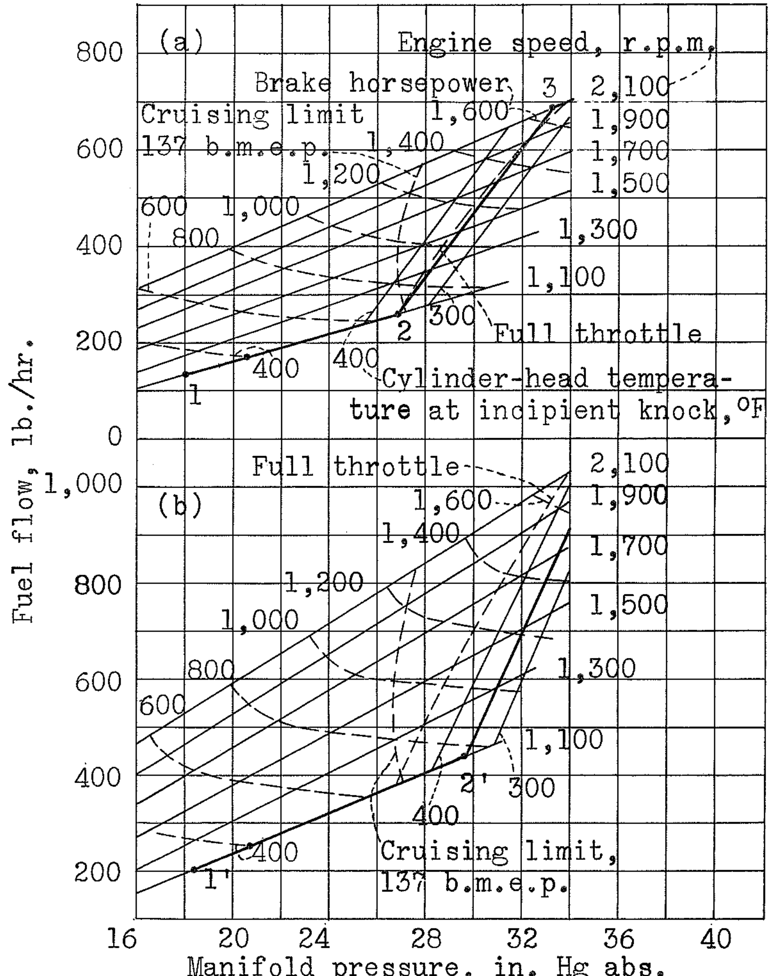


(a) Cost of net brake horsepower. (b) Cost of cooling. (c) Cost of air speed.

Figure 8.- Fuel consumption in flight at sea level.



(a) Fuel tanks empty.
(b) " " full.
Figure 9.- Flight mileage for conditions of figures 5 and 7 (sea level).



(a) Fuel-air ratio, optimum.
(b) " " " 0.10.
Figure 10.- Effect of manifold pressure, engine speed, and fuel-air ratio on rate of fuel consumption at 6,000 ft. Carburetor-air temp., 40 °F.; impeller gear ratio, 7.14.

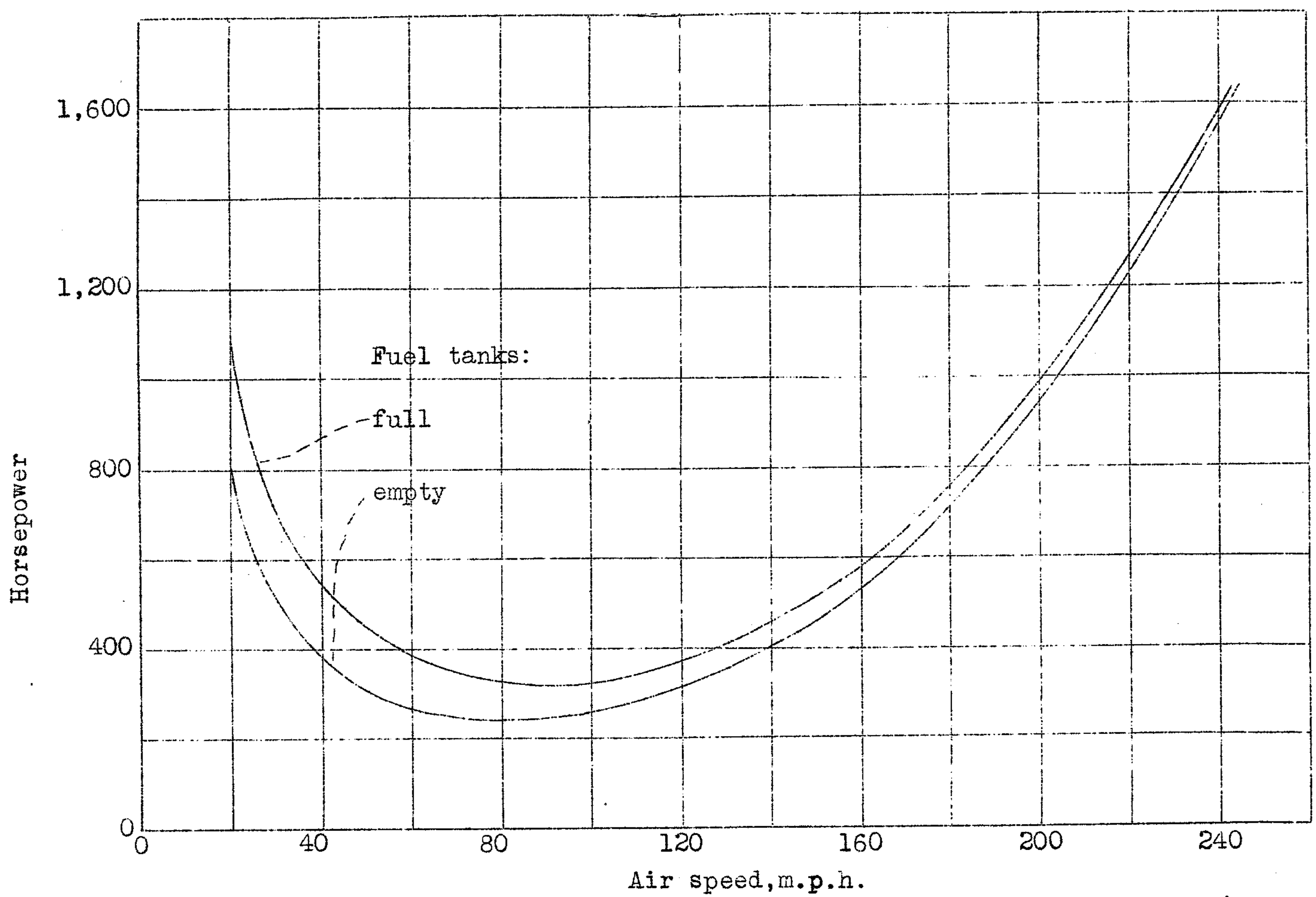


Figure 11.- Performance curves for Martin XB-10 at 6,000 feet.

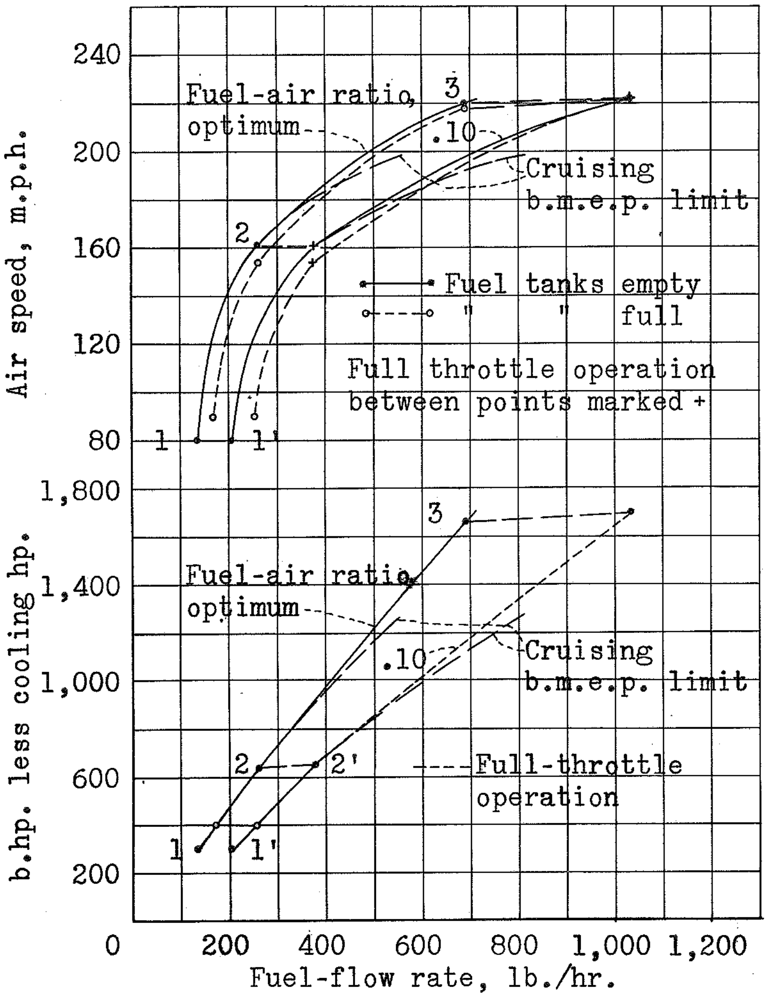
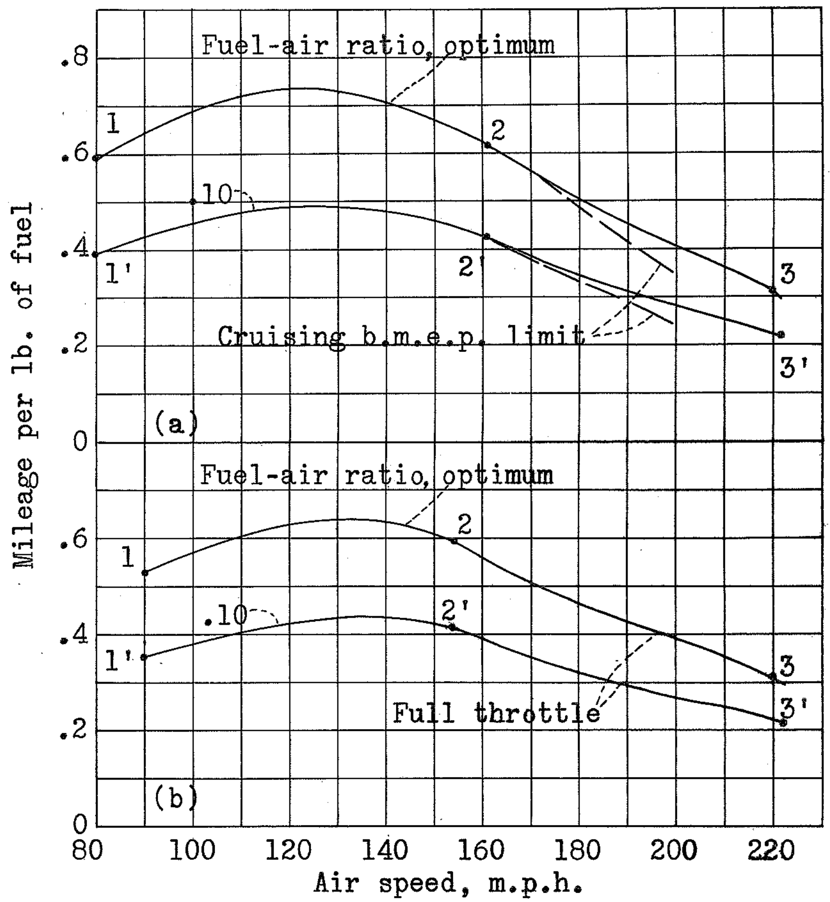


Figure 12.- Fuel consumption in flight (6,000 feet).



(a) Fuel tanks empty.
(b) " " full.

Figure 13.- Flight mileage for conditions of figures 9 and 11 (6,000 feet).